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A STUDY OF THE SEA BREEZE AT ATLANTIC CITY, NEW JERSEY USING TETROONS AS LAGRANGIAN TRACERS

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ABSTRACT

During July 1964 more than 90 constant volume balloon (tetroon) flights were made from the area of Atlantic City, N.J., with the primary purpose of delineating the sea breeze regime at that locale. The transponder-equipped tetroons were ballasted to float at a height of 500 ft., and were tracked by the U.S. Weather Bureau WSR–57 radar at Atlantic City. The tetroon trajectories are compared with surface winds and with (surface) geostrophic winds derived from pressure readings at four nearby weather stations. On the average, the tetroon direction differs from the surface wind direction by only a few degrees, but the tetroon speed exceeds the surface wind speed by a factor of nearly two. During pronounced sea breeze regimes the tetroon moves toward low pressure at an average angle of 20° during the morning hours and nearly 90° during the early afternoon hours. Both sequential tetroon releases and individual tetroon trajectories indicate a veering of the sea breeze flow during late afternoon and evening. The ratio of tetroon speed and geostrophic speed averages about 0.60 on non-sea breeze days and 0.35 on sea breeze days, with a tendency for the ratio to be at maximum in the late afternoon.

Tetroons released in the early morning into a gradient flow from the northwest exhibit a sharp turn to the north at the presumed position of the sea breeze front. On the basis of this turning it appears that the sea breeze front exists at sea prior to its arrival at the shore line, but the analysis is complicated by the fact that the tetroons are at some height above the surface. To the extent that tetroon trajectories represent air parcel trajectories, there is evidence that, frequently, sea breeze air is simply air from the land that has been modified by the sea surface. While the WSR–57 radar does not provide accurate tetroon-transponder height values, there is the suggestion of large vertical air motions near the sea breeze front and evidence that the sea air may, on occasion, override the land air so that the sea breeze frontal passage occurs first at some height above the ground.

The atmospheric diffusion to be expected in both sea breeze and non-sea breeze regimes is investigated through the simultaneous and sequential release of tetroons. In the case of instantaneous-point-source (relative) diffusion, the data suggest that the lateral and longitudinal standard deviations increase in proportion to about the first power of the downwind distance out to distances of the order of 10 km., but thereafter increase in proportion to about the 0.5 power. In the case of continuous-point-source diffusion, the data suggest that, at downwind distances from about 10 to 50 km., the lateral standard deviation is proportional to nearly the 0.85 power of the distance, and proportional to about the 0.2 and 0.9 power of the tetroon release interval on sea breeze and non-sea breeze days, respectively.

I. INTRODUCTION

Studies of the sea breeze may be divided into observational and theoretical categories. The theoretical aspects have been considered by Haurwitz [8], Schmidt [15], *Pearce* [14], Estoque [4], Fisher [6], and others. This paper deals solely with the observational aspects of the sea breeze and associated phenomena.

Extensive surveys of the sea breeze have been presented by Wexler [18] and by Defant [3]. These two articles also have excellent bibliographies to which the interested reader is referred. Much of the work on the sea breeze was carried out by the Dutch and Germans and no article

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would be complete without an acknowledgment of the pioneering work of van Bemmelen [16] and Koschmieder [9]. Within the United States there have been relatively few observational studies of the sea breeze, notably those of Craig, Katz, and Harney [2], Leopold [10], and, in particular, Fisher [5], and Frizzola and Fisher [7]. As far as is known, all previous studies of the sea breeze have been based upon fixed-point measurements (including pibals) or upon aircraft traverses. The use of free-floating, constant volume balloons (tetroons) for this purpose was first reported by Pack and Angell [12]. These latter experiments were carried out within the Los Angeles Basin during the late spring of 1963.

It was desired to complement this west coast investigation with a similar investigation on the east coast. A site was sought which met several criteria including, location in the east coast megalopolis strip, proximity to a nuclear reactor site, and a reasonably uncomplicated coastline. Atlantic City, N.J., satisfied these criteria, and since a U.S. Weather Bureau WSR–57 radar is located at the airport contiguous with the Federal Aviation Agency's National Aviation Facilities Experimental Center (NAFEC), this location offered the best combination of interesting problems and facilities for logistic support. For orientation purposes, figure 1 shows the position of Atlantic City relative to the large metropolitan centers. Note that in the vicinity of Atlantic City the coast line is oriented nearly northeast-southwest, but with numerous small bays and inlets. The area is flat (relief generally less than 100 ft.), and sandy loam with extensive areas of second-growth pine 30 to 60 ft. high alternates with farm and dairy sections.

In this paper emphasis is placed upon the information concerning sea breeze circulations to be obtained through the use of tetroons, but other matters of meteorological interest are discussed. For example, the tetroon trajectories have been compared with the surface geostrophic wind, and diffusion estimates have been derived from simultaneous and sequential release of tetroons. Inasmuch as the tetroon acceleration is known, studies may be made of the forces acting upon air parcels in the lower layers of the atmosphere. However, a thorough investigation of these forces has been reserved for a later paper.

2. PROCEDURES

The tetroons utilized were made of 2-mil mylar and had a nominal volume of 1 m.^{3} As at Los Angeles, transponders were attached to the tetroons so that the tetroons could be tracked at very low elevation angles without the interference of ground clutter. The exact manner in which the transponder system operates may be gleaned from the paper by Pack and Angell [12]. At Atlantic City the tetroons were ballasted to float at 500 ft. with about 30 mb. of superpressure through the use of an air-helium inflation procedure which negated the need for ballast as such. The flight package was completed with the addition of a parachute and a return tag. Inasmuch as the tetroon system possessed only a few grams of free lift at the surface, it was necessary to tow the tetroon aloft by means of a pilot balloon. A dynamite fuse, which burned at a uniform rate, was lit at the ground and this fuse then melted a loop of plastic which released the tetroon from the pilot balloon approximately at flight altitude.

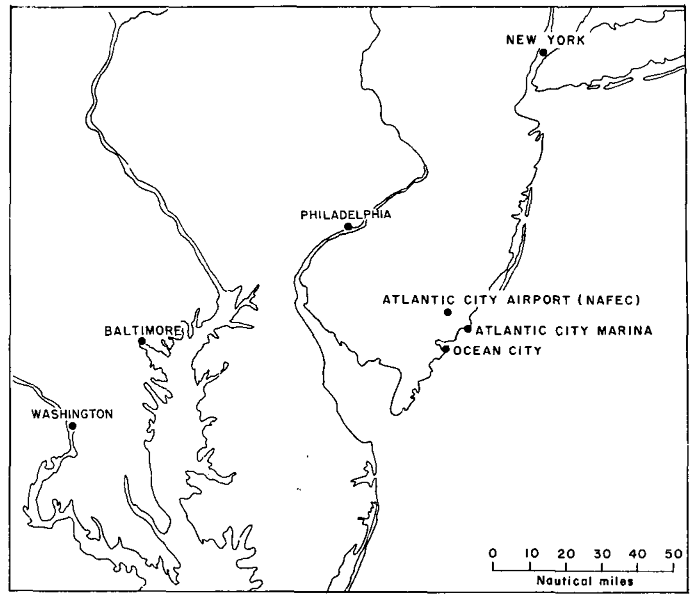

FIGURE 1.—The location of the Atlantic City Airport (ACY) and NAFEC, the Atlantic City Marina, and Ocean City, relative to the large metropolitan centers.

To ensure that tetroons could be released into either the land breeze or the sea breeze, release sites were set up at the Atlantic City Airport (about 10 mi. inland) and at Ocean City on the coast about 10 mi. southwest of Atlantic City (fig. 1). A large, closed van, equipped as a mobile tetroon inflation facility, was stationed at the latter site. Several of the tetroons released from Ocean City passed directly over the Atlantic City Airport and visual observation confirmed that the tetroon flight level was extremely low and probably, in the mean, close to the planned height of 500 ft. Unfortunately, as at Los Angeles, the radar used proved incapable of furnishing accurate tetroon heights because the inability to reduce radar power caused the transponder to be triggered over a considerable range of elevation angles.

Indirect evidence that the tetroons floated near the planned height of 500 ft. is offered in figure 2, wherein is shown the percentage of tetroon flights which were tracked by radar beyond a given range, and the range that would be expected under given refractive conditions if the tetroons were truly at a height of 500 ft. It is seen that there is a sharp drop in the number of flights tracked beyond 34 n. mi., a range about half way between that which would be expected if there were no refraction and that which would be expected if there were normal

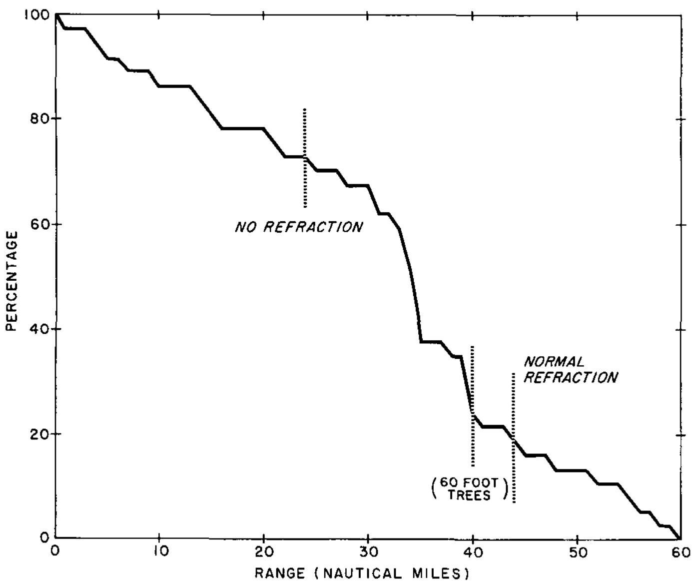

FIGURE 2.—Percentage of Atlantic City tetroon flights which were tracked by radar beyond a certain range, and the tracking range to be expected under given refractive conditions for tetroon flights at 500 ft.

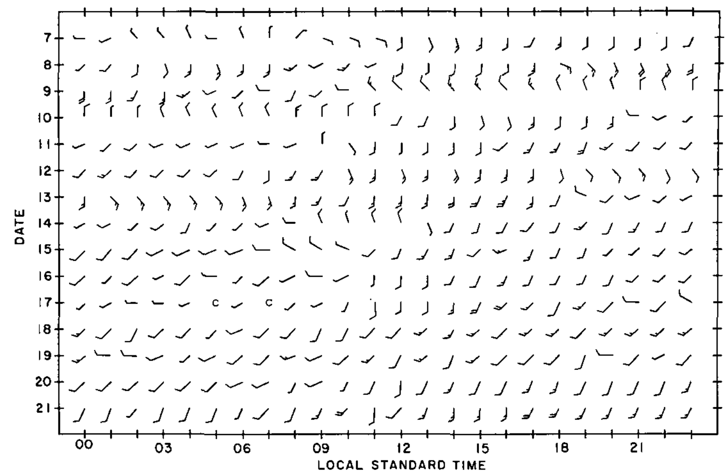

FIGURE 3.—Hourly winds at the Atlantic City Marina July 7–21, 1964. Wind speeds indicated in the conventional fashion, one-half barb equals 5 kt., one full barb equals 10 kt., etc.

refraction. It might be noted that the presence of 60-ft.-high trees would reduce the tracking range, under normal refractive conditions, from 44 to 40 n. mi., a value only 6 mi. different from the median range actually obtained. It is concluded that the tetroons flew close to the prescribed level of 500 ft.

Tetroon range and azimuth were obtained at 2-min. intervals. The tetroon range should be accurate to at least 0.1 n. mi. but it was not easy to obtain accurate tetroon azimuths because the radar triggered the transponder over a range of azimuth angles, and hence, the target appeared on the PPI scope as an arc. The "true" tetroon azimuth was estimated by averaging the azimuth values at the extremes of the arc, since previous comparisons with aircraft fixes (Pack and Angell [12]) have shown this procedure to be fairly satisfactory. Nevertheless, partly because of the presence of side lobes, some smoothing was desirable, and the data presented herein are based upon ranges smoothed over 6-min. intervals (the average of three 2-min. readings) and azimuths smoothed over 10-min. intervals (the average of five 2-min. readings).

3. TETROON TRAJECTORIES ON NON-SEA BREEZE DAYS

Figure 3 shows hourly winds at the Atlantic City Marina (fig. 1) during the period of the experiment. The arrival of a definite sea breeze at the Marina is quite evident on July 10, 11, 14, 15, 16, and 17, as evidenced by a sudden backing of the wind near noon. On the remainder of the days the synoptic situation was not favorable for the development of a well-defined sea breeze. In this section we shall analyze the tetroon trajectories on these non-sea breeze days. Table 1 provides the pertinent data concerning time of tetroon launch, flight duration, etc.

Figure 4 shows tetroon trajectories for the non-sea breeze days. Some of the simultaneous tetroon releases (fig. 14) were also considered to have been made on non-sea breeze days and have been included in the statistics. Flights 4–9 were released on July 9 and show a continuous veering of the wind with time in association with the passage of a cyclone to the east. Flights 8–12 show that there was very little change in trajectory direction during the night of July 9–10. Flights 32–45 were released on July 12. Flights 32–35 exhibit little variation in direction, but thereafter there was a backing of the wind direction with time as a cyclone moved in from the southwest. Rain began shortly after the release of flight 47 at 0148 LST on July 13. Flights 68–72 were released on July 18 when there was a tendency for gradient flow from the southwest, and flights 87–90 were released on July 21 under similar conditions. Flights 73, 74, and 80 were individual flights made on non-sea breeze days when simultaneous tetroon releases were the rule.

Of greatest interest on non-sea breeze days is a comparison of tetroon azimuth and speed with the direction and speed of the surface wind and (surface) geostrophic wind. In the case of the trajectories illustrated in figures 4 and 14, this was accomplished through determination of the mean trajectory azimuth and speed for each flight (from an average of the 2-min. azimuths and speeds) and comparison of these values with the mean surface wind direction and speed, for the time interval of tetroon flight, obtained from readings at hourly intervals at the Atlantic City Airport and at the Atlantic City Marina (for locations, see figure 1). To obtain the surface geostrophic wind, average pressures were determined (from hourly readings) at Atlantic City Airport (ACY), Millville

TABLE 1.—*Tetroon flights at Atlantic City, N.J., July 1964*

Date	Flight number	Launch site	Launch time (EST)	Tracking duration (minutes)	Tracking range (nautical miles)
July 6	1	ACY	2114	52	15.0
July 7	2	ACY	0829	578	54.0
July 7	3	ACY	1356	205	47.3
July 9	4	ACY	0728	210	38.5
July 9	5	ACY	0850	209	49.6
July 9	6	Ocean City	1526	242	57.8
July 9	7	do	1648	148	40.6
July 9	8	ACY	2128	192	34.7
July 9	9	ACY	2301	252	51.6
July 10	10	ACY	0203	158	32.8
July 10	11	ACY	0340	151	48.6
July 10	12	ACY	0518	178	63.3
July 10	13	ACY	0940	443	21.7
July 10	14	ACY	0940	0	0.0
July 10	15	ACY	1527	67	9.3
July 10	16	ACY	1700	186	25.9
July 10	17	ACY	1752	139	16.5
July 10	18	ACY	2047	234	51.3
July 10	19	ACY	2151	286	48.6
July 11	20	ACY	0115	138	37.8
July 11	21	ACY	0300	28	6.3
July 11	22	ACY	0353	98	27.0
July 11	23	ACY	0438	148	38.2
July 11	24	ACY	0623	42	4.0
July 11	25	ACY	0902	0	0.0
July 11	26	ACY	1026	348	32.2
July 11	27	Ocean City	1439	157	23.6
July 11	28	do	1654	145	38.2
July 11	29	do	1809	79	18.5
July 11	30	do	2121	172	47.7
July 11	31	do	2206	148	55.8
July 12	32	do	0118	196	59.1
July 12	33	do	0214	111	25.9
July 12	34	do	0436	152	41.8
July 12	35	do	0516	229	60.8
July 12	36	do	0826	266	45.0
July 12	37	do	0950	66	4.7
July 12	38	do	1147	258	63.1
July 12	39	do	1325	10	8.8
July 12	40	do	1431	78	14.2
July 12	41	do	1656	74	12.4
July 12	42	do	1713	142	25.0
July 12	43	do	2058	84	28.8
July 12	44	do	2204	78	28.2
July 12	45	do	2329	82	39.8
July 13	46	Ocean City	0029	88	48.8
July 13	47	do	0148	44	18.7
July 14	48	ACY	0802	0	0.0
July 14	49	ACY	0949	402	42.3
July 14	50	ACY	1226	64	9.6
July 14	51	ACY	1423	252	41.8
July 14	52	ACY	1659	26	5.1
July 14	53	ACY	1810	109	34.0
July 15	54	ACY	0515	32	6.6
July 15	55	ACY	0632	246	35.4
July 15	56	ACY	1012	195	26.5
July 15	57	ACY	1342	0	0.0
July 15	58	ACY	1455	108	30.8
July 15	59	Ocean City	1901	115	32.0
July 16	60	ACY	0610	244	28.9
July 16	61	ACY	1025	822	55.9
July 16	62	Ocean City	1406	381	48.3
July 16	63	do	1843	118	23.9
July 17	64	ACY	0545	196	21.1
July 17	65	ACY	0913	242	14.2
July 17	66	Ocean City	1324	186	38.3
July 17	67	do	1924	110	39.3
July 18	68	ACY	0617	114	30.1
July 18	69	ACY	0858	198	37.3
July 18	70	Ocean City	1427	106	24.0
July 18	71	do	1700	128	39.7
July 18	72	do	1943	54	13.9
July 19	73	ACY	0640	120	29.3
July 19	74	ACY	0945	150	39.7
July 19	75	ACY	1405	136	39.7
July 19	76	ACY	1413	113	34.3
July 19	77	ACY	1754	130	34.7
July 19	78	ACY	1759	113	33.0
July 20	79	ACY	0628	18	3.8
July 20	80	ACY	0753	62	35.6
July 20	81	ACY	1101	188	34.4
July 20	82	ACY	1108	172	36.0
July 20	83	Ocean City	1448	212	43.3
July 20	84	do	1458	225	44.6
July 20	85	do	1906	34	3.1
July 20	86	do	1911	31	6.5
July 21	87	ACY	0656	88	12.0
July 21	88	Ocean City	1016	60	2.6
July 21	89	do	1151	74	9.5
July 21	90	do	1857	54	6.5
July 23	91	ACY	0559	43	10.8
July 23	92	ACY	0622	50	8.4
Average				151	29.5

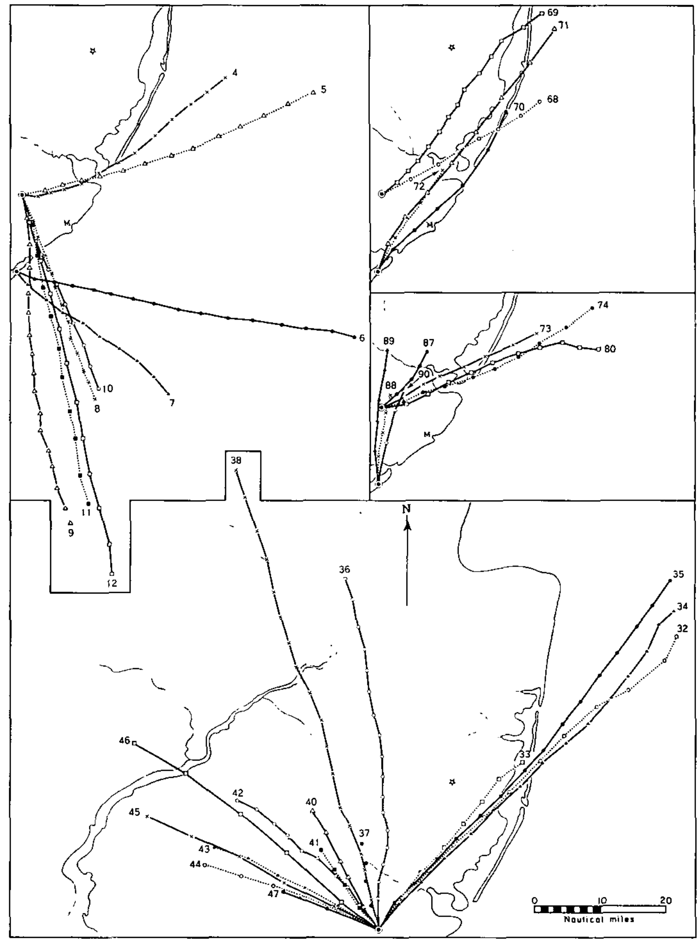

FIGURE 4.—Tetroon trajectories originating at Atlantic City Airport and Ocean City on non-sea breeze days. Tetroon position at 15-min. intervals; flight numbers plotted at ends of trajectories. The star shows the location of a lookout tower on relatively high ground; M is the location of the Atlantic City Marina.

(MIV), North Philadelphia Airport (PNE), and Lakehurst (NEL) (for locations see figures 7, 8) for the time interval of tetroon flight and a geostrophic wind was computed based on vector addition of the winds determined from the difference in pressure between ACY and PNE and between MIV and NEL.

There is some danger in deriving a geostrophic wind from such closely spaced stations (PNE is approximately 40 n. mi. from ACY while NEL is approximately 55 n. mi. from MIV) inasmuch as a small error in pressure will introduce a relatively large error in the derived geostrophic wind. Indeed, from a plot of the average pressure at these four stations, and other stations, there is evidence that ACY may be consistently a few tenths of a millibar too high and NEL consistently a few tenths of a millibar too low. However, the evidence is not sufficiently convincing to make a correction justifiable. If such errors exist, the west-east component of the geostrophic wind which we derived is too great. The alternative method of deriving the geostrophic wind from ana-

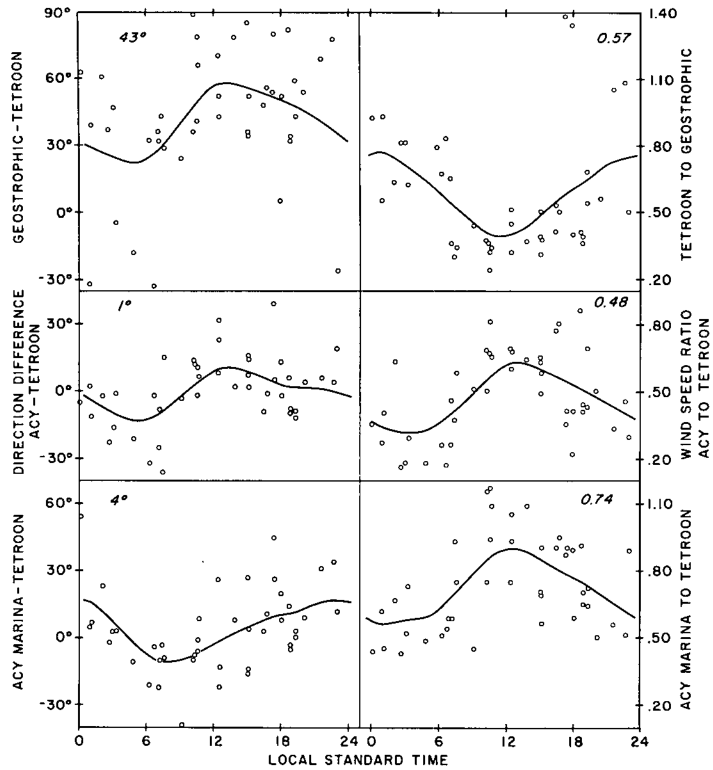

FIGURE 5.—On non-sea breeze days, (left) the difference between mean tetroon flight direction and the direction of the (surface) geostrophic wind, the Atlantic City Airport (ACY) wind, and the Atlantic City Marina wind as a function of time of day; (right) the corresponding wind speed ratios. The solid line represents a smoothed average of the individual difference values. The mean of all cases is plotted in the upper portion of each diagram.

lyzed 3-hourly surface maps was investigated and found inappropriate because of the disparity in time and space scales between the maps and the tetroon trajectories.

Figure 5 shows the various comparisons as a function of time of day. On the average, the angle between geostrophic wind direction and tetroon-derived wind direction (angle of indraft) was 43°, with the tetroon moving toward low pressure. However, the average angle of indraft varied from 22° at 0500 to 58° at 1300 LST. Thus, even on days when the sea breeze was not particularly in evidence, at heights of about 500 ft. there was considerable air flow toward low pressure during the early afternoon. In fact, based on the observed mean tetroon speed of about 17 kt., the average wind component in the direction of the pressure gradient at that time and height was nearly 15 kt. On the average, the ratio of tetroon-derived wind speed and geostrophic wind speed was 0.57, with the average ratio varying from 0.77 at 0100 to 0.39 at 1100 LST. Apparently, during the night the tetroons were above the surface inversion and hence, freed from the frictional influence of the ground, adapted more nearly to the geostrophic speed, whereas during the day the convection was sufficient to convey the frictional effect of the ground at least to tetroon height.

When the tetroon-derived wind direction is compared with the direction of the surface wind at ACY and at the Marina there is, on the average, only a 1° and 4° direction difference, respectively. This difference is negligible, particularly when it is noted that the surface wind direction was read to the nearest 10° at ACY and to the nearest 22½° at the Marina. There is a diurnal variation in the wind direction difference with the tetroon moving more directly toward low pressure than the ACY wind indicates during the afternoon and than the Marina wind indicates during the night. This diurnal variation is not dwelt upon here because of the small sample and the complexities introduced by the different frictional effects to be expected over land and sea. However, the overall lack of evidence for a veering of the wind with height (Ekman spiral) suggests either that the surface boundary layer extended to a height of hundreds of feet or that steady-state conditions simply did not exist.

While the tetroons faithfully reflect the surface wind directions, they do not reflect the surface wind speed. On the average, at ACY, the ratio of surface to tetroon-derived wind speed was 0.48, whereas at the Marina the ratio was 0.74. The difference in these two ratios indicates the different frictional effects of land and sea. At both locations there was a large diurnal variation, with the ratio at a minimum about 0300 and at a maximum about 1300 LST, or just what would be expected from the diurnal variation in vertical mixing. The average difference between tetroon-derived wind speed and surface wind speed was 9.1 kt. at ACY and 5.2 kt. at the Marina. With the assumption that the tetroons were floating at a height of 500 ft. and that the (dynamic) eddy viscosity had a value of about 10^2 gm. cm.$^{-1}$ sec.$^{-1}$, the average stress (at a height near 250 ft.) turns out to be 3.1 and 1.8 dynes cm.$^{-2}$ at ACY and the Marina, respectively. With the additional assumption of negligible particle acceleration, the rate of change of stress with height is proportional to the vector difference between wind and geostrophic wind. Through the use of the above data it is thereby estimated that the stress at the ground should be 0.7 dynes cm.$^{-2}$ larger than the indicated values of 3.1 and 1.8 dynes cm.$^{-2}$. Thus, the derived value of the surface stress is of the right order of magnitude.

Nevertheless, the assumption of negligible particle acceleration is a dubious one. On the non-sea breeze days, when there was little change in trajectory direction with time, a good estimate of the acceleration may be obtained from the speed change with time. Even if the tetroon speed is averaged over 1 hr., and the acceleration determined from the change in speed in 1 hr., the mean value of the acceleration is 2.1×10^{-4} m. sec.$^{-2}$, in comparison with a mean value for the Coriolis force of 8.3×10^{-4} m. sec.$^{-2}$ and for the pressure gradient force of 14.6×10^{-4} m. sec.$^{-2}$ on these same flights. Inasmuch as the mean value of the acceleration undoubtedly has been underestimated, both in the averaging procedure and by the specification of

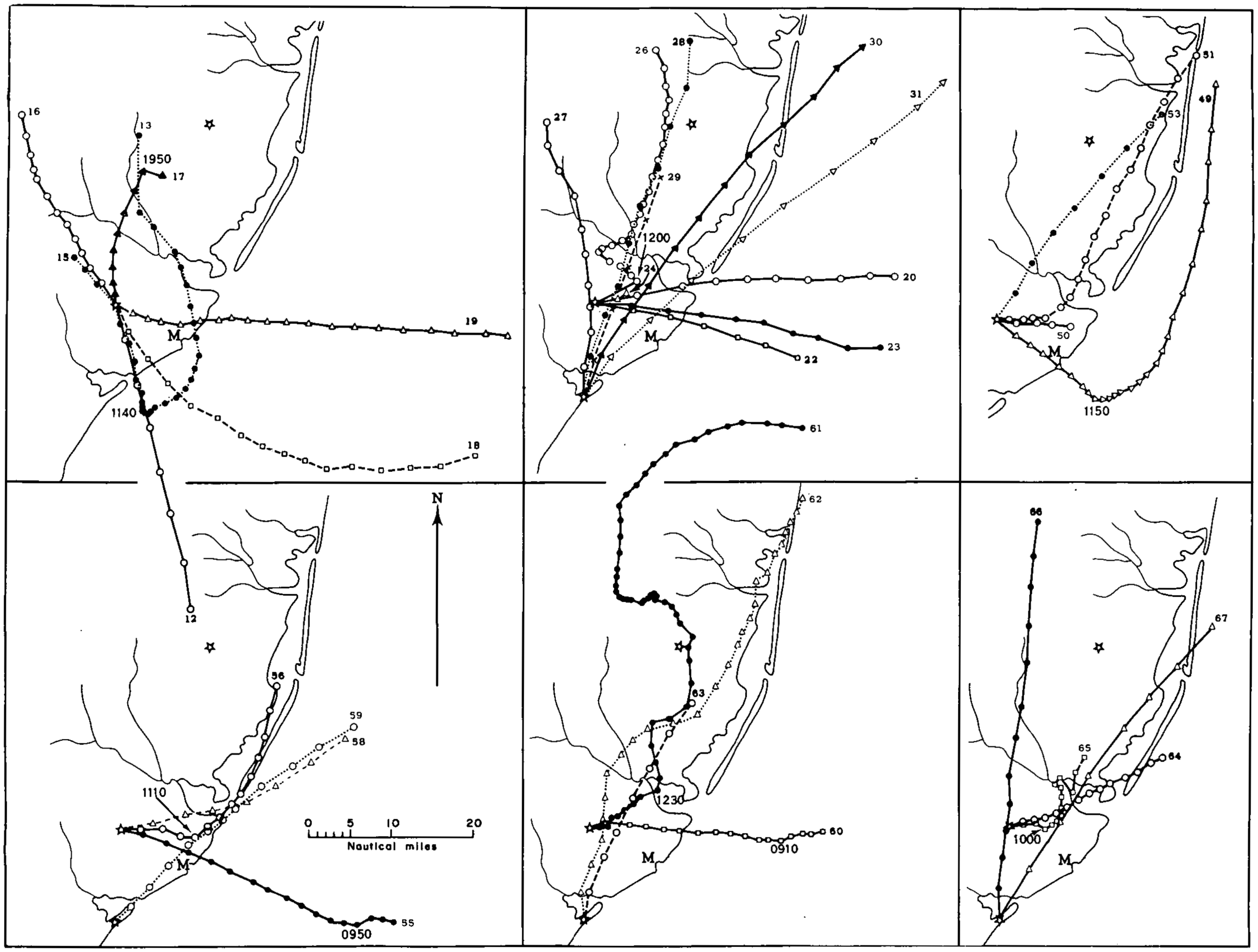

FIGURE 6.—Tetroon trajectories originating at Atlantic City Airport and Ocean City on sea breeze days (July 10, 11, 14, 15, 16, 17). The times (local standard) of pronounced tetroon direction changes are indicated along some trajectories. Otherwise, see legend for figure 4.

the synoptic situation, one certainly can *not* state that the acceleration is one order of magnitude smaller than the Coriolis and pressure gradient forces and therefore negligible.

4. TETROON TRAJECTORIES ON SEA BREEZE DAYS

Tetroon trajectories for the 6 days classified as sea breeze days are presented in figure 6. It will be noted that, unlike those plotted in figure 4, many of the trajectories in figure 6 are characterized by large changes in direction and speed, as befits the more complex flow of the land and sea breeze regime. While these trajectories are of interest in themselves, a full appreciation of the usefulness of the data derived therefrom can only be obtained through collation of the tetroon trajectories with conventional, fixed-point data. Consequently, for each of the sea breeze days, small "synoptic" maps have been plotted at 3-hr. intervals, as shown in figures 7 and 8. Hourly winds at ACY, ACY Marina, MIV, PNE, and NEL are indicated on these maps, as are tetroon positions at half-hour intervals. In order to save space, three separate hourly maps have, in effect, been overlayed on the same map, with the data appropriate to a particular map time distinguished by the type of wind-direction arrow or mode of trajectory representation. Since the geostrophic wind changed slowly, only the value at map time has been plotted.

In this section, then, we shall give a brief description of the tetroon trajectories on particular sea breeze days and the points of special interest delineated thereby. Unless otherwise noted, reference should generally be made to either figure 7 or figure 8. In all cases the times are local standard (in this case Eastern Standard Time) and the distances are given in nautical miles.

July 10.—On this date the geostrophic wind backed from west-northwest at 1200 to west-southwest at 1800. With such a geostrophic wind direction the sea breeze is usually well defined, and indeed, flight 13, released from ACY at 0940, yielded the most pronounced land-sea breeze reversal of the Atlantic City series. Initially this flight followed exactly the same path as did flight 12 but the tetroon began to move toward the southeast at 1138 and toward the northeast at 1158, with an average speed during the time interval of less than 2 kt. If the sea breeze is defined as a flow which displaces the tetroon to the north, then the sea breeze made its appearance at the Marina (at 1129) before it affected the tetroon at a position 10 mi. to the south-southwest of the Marina. Of course, there is the complication that the tetroon was about 500 ft. above the surface and we shall deal with this problem later. Flight 13 moved inland 2 mi. northeast of the Marina (Brigantine area) at about 1430, or 3 hr. after the arrival of the sea breeze at the Marina. Thus, insofar as a tetroon follows the motion of individual air parcels, there is evidence that the sea breeze air moving into the Brigantine area at 1430 was the same air that was over ACY at 0940. It is thus of interest that the surface temperature at ACY at 1000 was 73° F. while the air temperature at the Marina at 1500 was also 73° F. so that, if the tetroon trajectory is assumed to represent the surface air trajectory, the pertinent air parcel need not have undergone any temperature change. It must never be forgotten that the chief advantage of the tetroon lies in its ability to delineate, at least approximately, the trajectories of air parcels. Sea air apparently reached ACY between 1400 and 1500 (with a 1° F. temperature fall and a 6° F. dew point rise between these two times) or at about the time flight 13 moved inland over the coast. The homogeneity of the wind-direction data is emphasized by the agreement in direction among the ACY wind, the Marina wind, and the tetroon-derived wind at 1500 and 1600.

Flight 15 was released from ACY at 1527, or approximately 1 hr. after the arrival of sea air at ACY. This flight moved toward the northwest, in agreement with the wind at ACY and the Marina and the direction of travel of flight 13. These data all indicate an angle of about 135° between low-level wind and geostrophic wind, i.e., the wind had an anti-geostrophic component. There must have been a line of convergence between MIV and ACY at 1500 and 1600 since MIV reported a west-northwest wind at these times. The termination of flights 13 and 15 may well have been associated with this line of convergence.

Flight 16, released from ACY at 1700, moved initially to the northwest, although exhibiting a slight veering from the direction of travel of flight 15. At 1900 the wind at PNE was west-northwest so that the sea breeze front must have been between PNE and the position of flight 16, which at that time was moving toward the north-northwest at a point 20 mi. south-southeast of PNE. The wind at PNE veered to south at 2100, or at about the time flight 16 would have arrived at the station if it had remained airborne. The location of the tetroon in the forefront of the sea air at the time of flight termination is consistent with the rate of progression of the sea breeze front (6 kt. based on the time of wind shift at ACY and PNE), the average speed of 8 kt. for flight 16, and the fact that flight 16 was released approximately 1 hr. after the sea breeze front passed ACY.

Flight 17, released from ACY at 1752, moved more directly to the north than the two previous flights, illustrating the influence of the Coriolis force on the sea breeze flow. At 1953, and at a point 17 mi. north of ACY, flight 17 moved abruptly to the east-southeast (fig. 6). At first it was believed this was a sea-land breeze reversal but it now appears that the sudden shift in direction was induced by a thunderstorm. For example, ACY reported towering cumuli to the north at 1900, and the ACY wind direction shifted from 160° at 2000 to 360° at 2044 with lightning reported to the north. The ACY wind shifted to west at 2117 and to south at 2158.

Flight 18 was released at 2047, or just after the ACY wind shift occurred. This flight moved to the southeast even though, at 2100, Marina had a west wind and PNE and NEL south winds. Examination of the Marina wind trace shows that the wind at this site was north of west from 2100 to 2115. The wind shift experienced by flight 17 at 1953, by ACY at 2044, and by the Marina at 2100 is consistent with a wind shift line, oriented approximately east-northeast to west-southwest, moving south-southeastward at about 18 kt. After the wind shift to the north, ACY reported winds of 6 kt. gusting to 13 kt. so that the wind shift line apparently was moving considerably faster than the surface wind. However, the average wind speed for the first half hour of flight 18 was 16 kt., so that the wind shift line could well have been moving with the wind at the tetroon flight level of 500 ft. This illustrates the utility of tetroons for obtaining data in regions where no fixed-point observations are available and also for obtaining data at some height above the surface. Finally, it might be noted that, while at ACY the wind remained north of west for only 33 min., and at the Marina for only 15 min., the trajectory of flight 18 was from north of west for 2½ hr. This forcibly indicates the inertia of "blobs" of air and the difference in periodicity to be expected in Lagrangian and Eulerian frames of reference.

July 11.—On July 11 the geostrophic wind was from the southwest. Perhaps because of this orientation the sea breeze occurred rather early in the day, with the Marina wind becoming southeasterly at 0900 and the ACY wind becoming quite strong from the east-southeast at 1100. Flight 26, released from ACY at 1026, moved initially to the north-northeast. It was then caught in an updraft and visually was observed to rise to a considerable height. At first this flight was tracked by radar with difficulty and was not well positioned until 1200, when the flight was east-northeast of ACY and moving to the northwest in good agreement with the

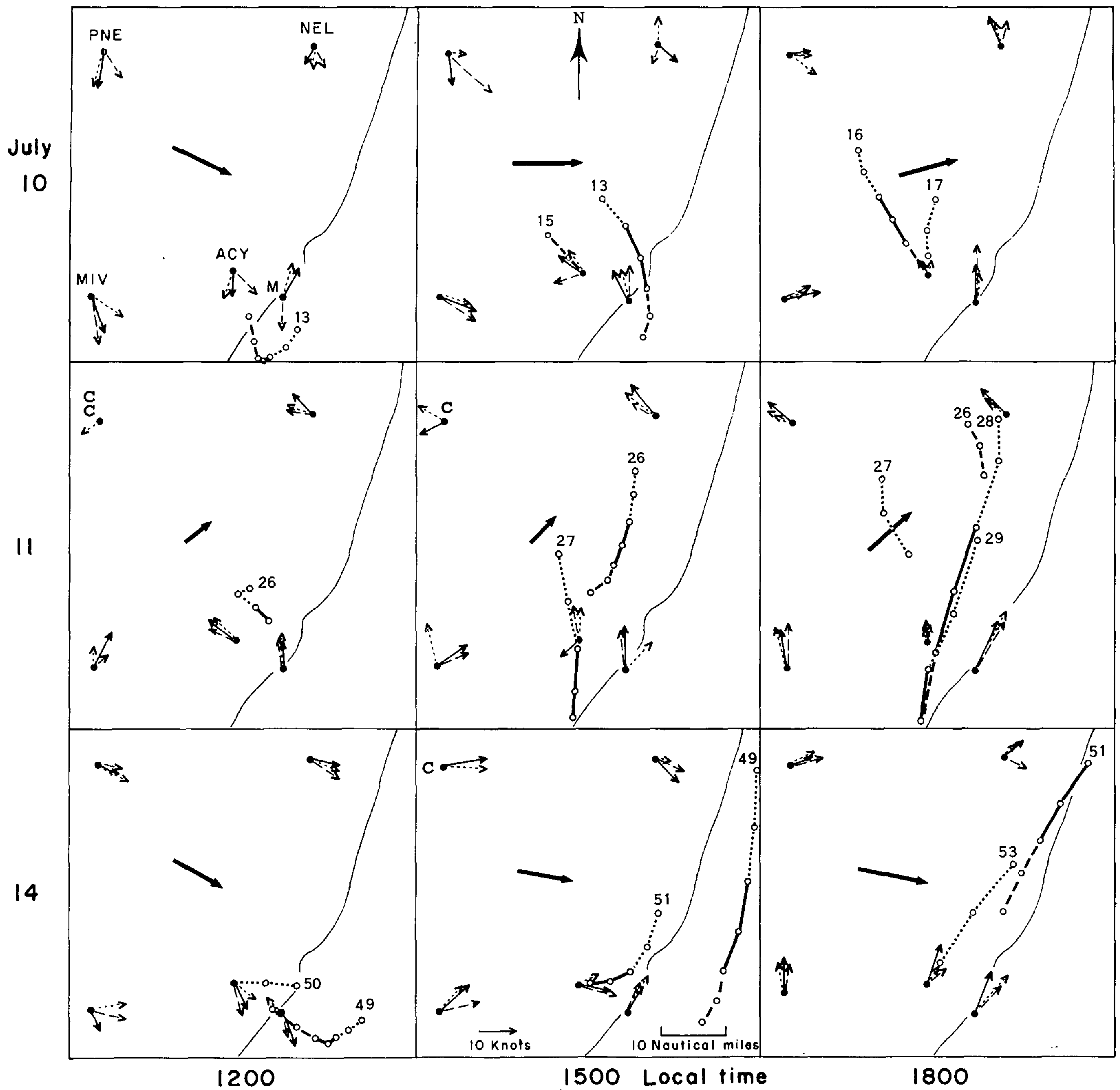

FIGURE 7.—Tetroon trajectories (circles) and corresponding wind data for Atlantic City Airport (ACY), Atlantic City Marina (M), Millville (MIV), North Philadelphia Airport (PNE), and Lakehurst (NEL), for July 10, 11, and 14. Solid arrows represent winds at indicated map time and solid trajectories represent tetroon trajectories from ½ hr. before to ½ hr. after map time. Dotted arrows and dotted trajectories refer to a time 1 hr. later, dashed arrows and trajectories refer to a time 1 hr. earlier (c indicates a calm). The heavy arrow shows the geostrophic wind at map time (speed scale one-half that of the station winds). Tetroon flight numbers plotted at ends of trajectory segments.

surface wind at ACY. The maximum inland penetration of flight 26 occurred at 1300, after which time the flight moved to the northeast and then to the north. Presumably, the 1300 position (about 7 mi. north of ACY and just south of the Mullica River) marks the approximate location of the sea breeze front at this time and place. Flight 26 again turned to the northwest a few miles south of NEL (Toms River area), in agreement with the NEL wind direction. Hence, this flight suggests that the sea breeze had progressed farther inland in the region of the river valleys than in the intervening regions of slightly higher ground.

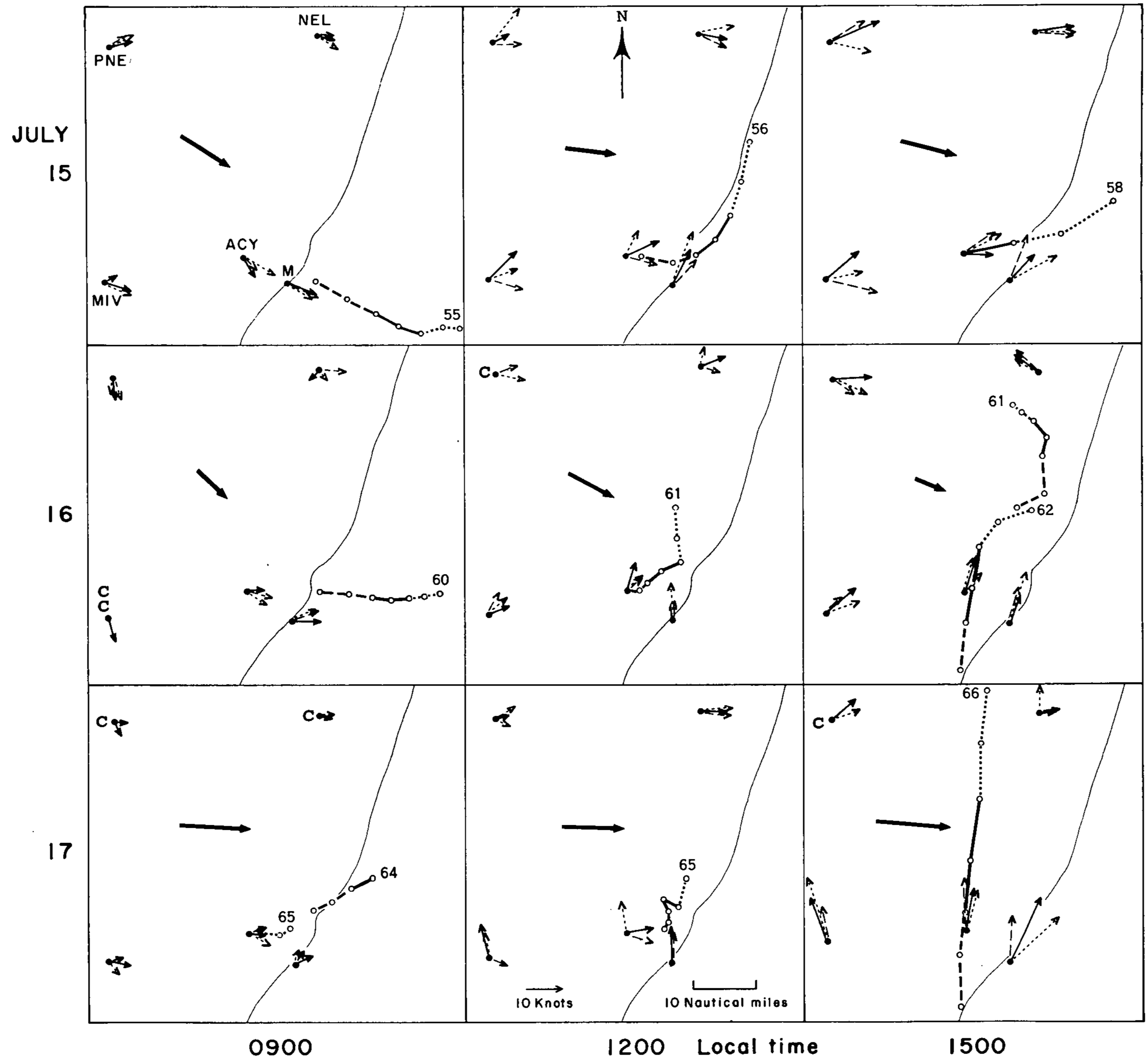

FIGURE 8.—Same as figure 7, for July 15, 16, and 17.

Flight 27, released from Ocean City at 1439, passed directly over ACY at 1534. This is particularly intriguing because the ACY wind did not shift from northeast to south until 1545, or 11 min. later. Thus the tetroon moved overhead from the south at a time when the surface wind was still northeast. It is apparent from the 1500 map of figure 7 that this northeast wind was quite anomalous and apparently was associated with a nearby thunderstorm. Flight 27 certainly was embedded in sea air but it is not certain whether the northeast flow at ACY involved sea air or not. In any event, when the ACY wind shifted to south, there was a temperature drop of only 1° F., so that there is no great difficulty in visualizing the sea air from Ocean City temporarily overriding the northeast air flow at ACY. After passing north of ACY, flight 27 moved to the north-northwest. This movement is in agreement with a rather deep inland penetration of the sea breeze, as exemplified by the east-southeast wind at PNE from 1600 to 1900. Such a pronounced inland penetration would be expected because the afternoon geostrophic wind was from the southwest rather than from the west.

Flights 28, 29, 30, and 31 were released from Ocean City at 1654, 1809, 2121, and 2206, respectively. These trajectories veered in direction with time, again illustrating the influence of the Coriolis force upon the sea breeze flow (fig. 6). The direction of these flights agreed well with the Marina wind direction, but on the average the flights moved toward low pressure at an average angle of about 50°. One might note the evidence, at 1800 and 1900, for horizontal divergence just inland from the coast occasioned by southeast or south-southeast winds at MIV, PNE, and NEL, and south-southwest winds nearer to the coast.

July 14.—Flight 49, released from ACY at 0949, moved initially to the southeast, in general agreement with the geostrophic wind direction at that time. Because of this agreement, the subsequent direction shift associated with the sea breeze appears less abrupt than that on July 10. The tetroon first moved toward the north at 1156 (recall that it was 1158 in the case of flight 13), while at the Marina the wind shift from northwest to southeast occurred at 1240. Therefore, in this case the sea breeze affected the tetroon, at a position 7 mi. southeast of the Marina, before the sea breeze made an appearance at the Marina. After the turn, flight 49 moved almost due north just off the coast. At 1600 the tetroon indicated a south wind of about 15 kt. at a point 15 mi. east of NEL where the wind was west at 4 kt.

Flight 50 was released from ACY at 1226, or 14 min. before the arrival of the sea breeze at the Marina. This flight moved nearly straight east for 9 mi. and then disappeared from the radar scope. The 1300 map shows that at this time the winds at ACY and the Marina were directly opposed and it is likely that the termination of flight 50 was induced by the sea breeze, since, from theoretical modeling, Estoque [4] has found evidence for descending motion ahead of the leading edge of the sea breeze.

Flight 51, released from ACY at 1423, moved at first to the east and then to the northeast. The turn to the north occurred at 1524 at a point 6 mi. east of ACY. This movement of the tetroon into the sea breeze convergence zone was also shown by a doubling of the tetroon speed. Thus, nearly 3 hr. after the sea breeze arrived at the Marina, the sea breeze apparently had reached a point only about 5 n.mi. inland, yielding an average speed of movement of 1.7 kt. The wind at ACY backed gradually from a direction of 280° at 1500 to a direction of 200° at 1800. However, between 1700 and 1800 the temperature decreased by 6° F. and the dew point rose by 6° showing that the sea breeze arrived at ACY sometime during this period. With the assumption that the sea breeze front passed ACY at 1730, the front progressed inland from the Marina at an average speed of 1.8 kt. in good agreement with the value derived from the tetroon trajectory. It is not apparent why the sea breeze progressed inland so much more slowly on July 14 than on July 10, the geostrophic wind being quite similar on the two days.

Flight 53 was released from ACY at 1810, or soon after the sea air reached ACY. This flight moved straight to the northeast, apparently embedded within sea air the whole way. The trajectory direction agreed well with the wind direction at the Marina, ACY and NEL, but made an angle of 50° with the geostrophic wind direction.

July 15.—Flight 55, released from ACY at 0632, moved to the east-southeast, in general agreement with the geostrophic wind and the winds at ACY and the Marina. This flight turned slightly toward the north at 0940 and at a distance of more than 20 mi. from the coast. It is unfortunate that this flight could not be tracked farther to see if this turn was definitely associated with the sea breeze which arrived at the Marina at 1030.

Flight 56 was released from ACY at 1012, or 18 min. before the arrival of the sea breeze at the Marina. Initially, this flight moved to the east-southeast, but at 1108, at a point 3 mi. north of the Marina, the flight turned toward the north. This northward turning of flight 56 at 1108 was undoubtedly connected with the sea breeze front which passed the Marina at 1030. Because of the fact that the geostrophic wind remained west-northwesterly throughout the day, it does not appear that sea air ever reached ACY on this date; the temperature and dew point remained quite constant all afternoon. Between 1400 and 1600 the Marina wind veered and it may be noted that flight 58 (released from ACY at 1455) moved considerably to the east of flight 56. At 1655, at the Marina, there was a sudden shift (reason unknown) from a west wind to a south-southwest wind. As a result of this shift back to the usual sea breeze flow, flight 59 (released at 1901 from Ocean City) yielded a typical, early evening sea breeze trajectory (fig. 6).

July 16.—Flight 60, released from ACY at 0610, at first moved nearly straight east but then began to move toward the east-northeast at 0904 (recall that it was 0940 in the case of flight 55) at a point about 16 mi. from the Marina. As on July 15, there is some question as to whether this turn at 0904 was associated with the sea breeze flow. At the Marina the sea breeze appeared with an abrupt wind shift at 1023.

Flight 61 was released from ACY at 1025, or at almost the exact instant the sea breeze arrived at the Marina. The tetroon moved generally to the east but was not well positioned until 1050 when it was 2.1 mi. east of the launch site. The tetroon then started to move toward the northeast, but the trajectory was irregular, perhaps because of changes in tetroon height.

At 1234, flight 61 started to move to the north-northwest and continued this movement until 1330. The turn to the east-northeast at 1330 presumably shows that the sea breeze only extended about 10 mi. inland at that time. It is likely that the sea breeze front arrived at ACY between 1300 and 1400, during which time the wind backed from 230° to 200°, the wind speed increased from 6 to 9 kt., and the dew point increased by 3°F. The sea air was not long at ACY inasmuch as between 1500 and 1600 the wind veered, the temperature increased by 4°F., and the dew point decreased by 3°F. Thus, the limited inland penetration of flight 61 to the north of Atlantic City appears quite compatible with the weak and temporary sea breeze regime noted at ACY.

Subsequent to the trajectory turn at 1330, flight 61 skirted the low hills on which the forest lookout tower is located, and then moved almost directly to the west in the Toms River area. This movement is in accord with the wind direction at Lakehurst and suggests that, at least under certain conditions, the sea breeze may extend much farther inland in the Toms River area than in the Atlantic City area despite the more favorable coastal orientation in the latter region. Throughout the period 1600 to 2000 the winds at Lakehurst and North Philadelphia were nearly directly opposed (fig. 9). Accordingly, the northward turn of flight 61 at 1800 undoubtedly indicates the extent of the sea breeze penetration (20 mi. inland) at this time and in this area. Flight 61 moved 10 mi. northward, then about 20 mi. northeastward, and finally turned to the east and moved out over the sea in the vicinity of Asbury Park at 2230, presumably in the land breeze. The Lakehurst wind was calm at 2100 but became westerly at 2200, in general agreement with the tetroon trajectory. Flight 61 is an excellent example of the useful information to be obtained from tetroon trajectories in that, not only is the approximate trajectory of the air obtained, but the location of meso-scale features such as the sea breeze front may be determined without resort to a detailed, fixed-point, meso-scale network of wind stations.

Flight 62, released from Ocean City at 1407, moved very nearly over ACY, thus confirming that sea air actually reached ACY on this day. This flight then turned to the northeast at the same location where flight 61 made its turn northeastward. Apparently, between 1330 and 1600 the sea breeze front remained almost stationary in this region. However, flight 62 did not follow the westward path of flight 61 in the Toms River area but rather moved to the north-northeast (fig. 6).

Flight 63, released from Ocean City at 1844, moved nearly straight northeast, and exhibited none of the trajectory irregularities of flights 61 and 62. Apparently, by this time of day the driving force for the sea breeze circulation has become negligible and the trajectories reflect only the influence of the Coriolis force upon the original sea breeze circulation.

July 17.—Flight 64 was released from ACY at 0545 and moved directly to the east-northeast, moving toward low pressure at an angle of about 25°. Flight 65 was released from ACY at 0913 or at about the time the sea breeze arrived at the Marina. This flight moved first to the east, then to the southeast, and finally turned to the northeast at 0958 at a point half way between ACY and the Marina. At 1000 the ACY wind was west-northwest whereas the Marina wind was south-southwest so that there is every

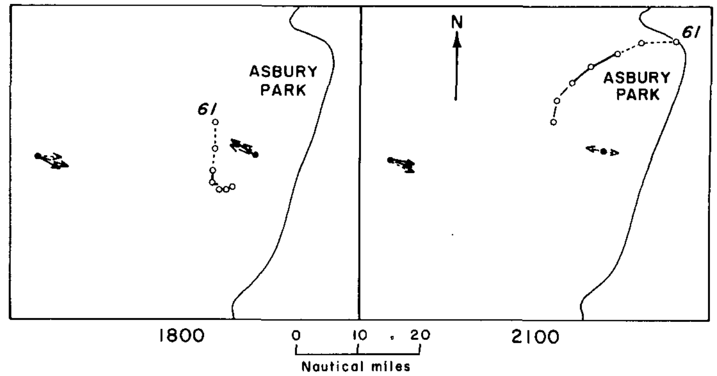

FIGURE 9.—Portion of trajectory of flight 61 on July 16 showing the inland extent of the sea breeze and the reversal to a land breeze in the vicinity of Asbury Park, N.J. Otherwise, see legend for figure 7.

evidence that the turn to the north was due to the arrival of the tetroon near to the position of the sea breeze front. As in the case of flight 61, the trajectory of flight 65 was irregular after its turn to the northeast. Once again, this was probably due to an involvement with the sea breeze convergence zone. At 1200 ACY reported towering cumuli in the area and at 1207 the elevation angle of the tetroon began to increase abruptly. This increase in elevation angle was unique in that, for the only time in the Atlantic City experiments, the tetroon could not be located at zero elevation angle. From the upper and lower edges of the pip on the RHI scope, the best estimate of the tetroon height was about 15,000 ft. During this time the tetroon moved to the southeast, apparently embedded in the upper-level flow. Thus there appears to be no doubt that the tetroon was forced to great heights by upward air motions induced by the convergence at the sea breeze front. Wallington [17] has also found evidence (from gliders) of large vertical motions in the sea breeze convergence zones.

Flight 66 was released from Ocean City at 1324 and moved due north passing over ACY at about 1400. Note that this trajectory was directed almost exactly perpendicular to the surface geostrophic wind. The Lakehurst wind backed from west to south between 1500 and 1600 and the tetroon passed west of Lakehurst, moving north, about 1615. On the other hand, at ACY the sea breeze front passed between 1200 and 1300 while flight 66 passed over the station at about 1415. Thus, the tetroon appears to have been overtaking the sea breeze front between ACY and Lakehurst.

Flight 67, released from Ocean City at 1924 moved directly to the northeast, again showing the effect of the Coriolis force upon the sea breeze.

5. ANALYSIS OF THE SEA BREEZE FLOW

One of the valuable pieces of information we hoped to derive from the tetroon flights concerned the orientation of the sea breeze front at sea and the manner in which this

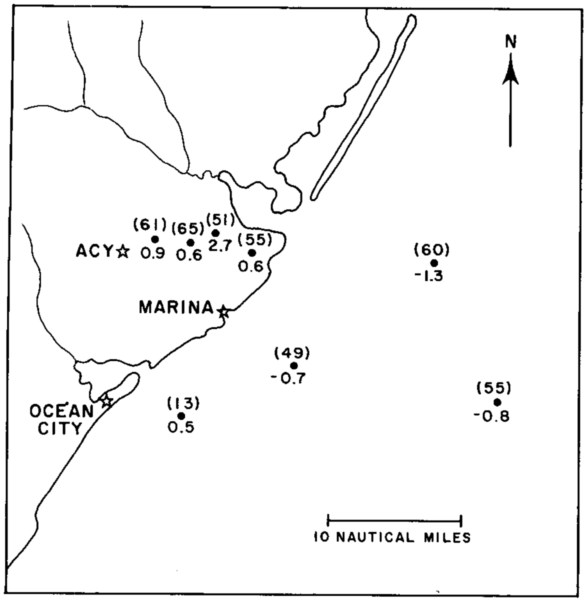

FIGURE 10.—The southernmost points of individual tetroon trajectories (tetroon flight numbers in parenthesis) and the time difference (in hours) between tetroon turn to the north and arrival of the sea breeze at the Atlantic City Marina (positive number indicates Marina wind shift occurred first).

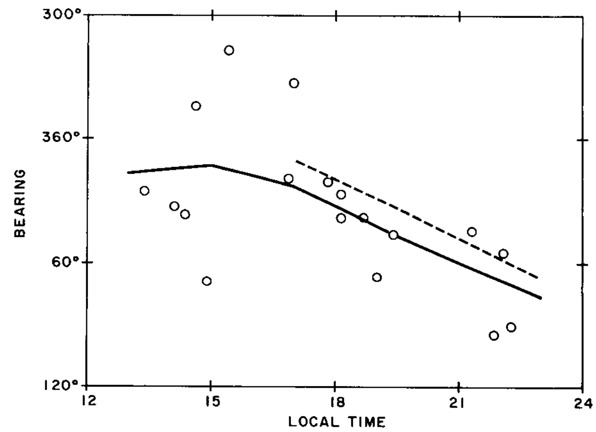

FIGURE 11.—Bearing of the end-point of tetroon trajectories, as a function of tetroon release time, for flights released on sea breeze days. The solid line represents a smoothed average of the individual bearings, the dashed line the change in bearing associated with an oscillation of pendulum day period.

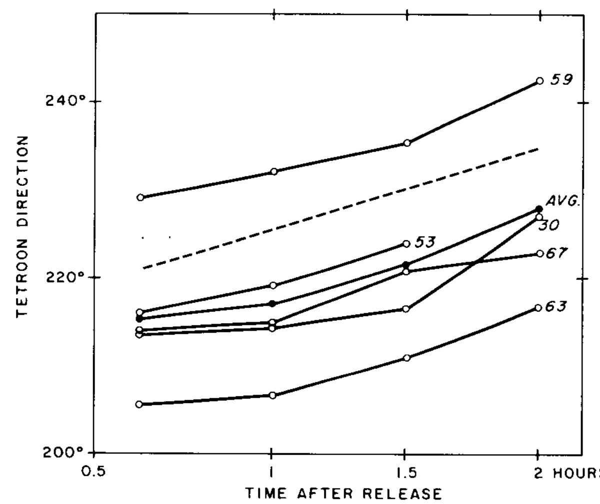

FIGURE 12.—Tetroon trajectory direction (½ hr. average) as a function of time after release for flights released between approximately 1800 and 2100 LST on sea breeze days. The dots represent the average trajectory direction, the dashed line the change in direction associated with an oscillation of pendulum day period. Flight numbers indicated at ends of lines.

sea breeze front moves landward. In general, our knowledge of these features at sea is limited because of the difficulty of obtaining observations over the water. The work of Fisher [5] is unique in this respect since his analysis of the sea breeze included observations from Block Island (approximately 20 mi. off the Rhode Island coast) and from a nearby ship. The consensus is that, if the gradient wind is negligible, the sea breeze develops very close to shore and progresses landward and seaward, whereas if there exists a gradient flow from land to sea, the cool sea air is maintained at sea by frictional interaction with the gradient flow until a veritable cold front is established. Since we have defined sea breeze days on the basis of an abrupt wind shift at the Atlantic City Marina, it is apparent that in figures 7 and 8 we should be dealing with a sea breeze of the latter type. With the possible exception of July 11, the direction of the geostrophic (gradient) wind in figures 7 and 8 is compatible with this type of sea breeze.

An interesting feature of the previous discussion involved the time difference between the arrival of the sea breeze at the Atlantic City Marina and the initial northward movement of the tetroon, the latter being taken, arbitrarily, as the position of the sea breeze front at the given time. Any discussion of this time differential is complicated by the fact that the tetroon was approximately 500 ft. above the surface and hence much depends upon the slope of the sea breeze front and the height to which the sea air extended. In order to clarify the problem, figure 10 shows the position of the tetroon flights when they first made a turn to the north, and the difference between the time of turning and the arrival of the sea breeze at the Atlantic City Marina. For example, flight 49, at a position 6.8 mi. southeast of the Marina, made a turn to the north 0.7 hr. before the Marina wind shifted so that in this case the slope of the sea breeze front must have exceeded 1 in 70. Conventional observations have shown that quite often over land, the sea breeze air arrives first at some height and, indeed our own flight 27 suggests this same phenomenon. However, over the sea one would certainly not expect a sea breeze front with an inverse slope, and about all that we can say with regard to figure 10 is that if the tetroons had been flown just above the sea surface they would have encountered the sea breeze front closer to the shore and at an earlier time. Thus, flight 13 does not necessarily imply that the sea breeze front impinged on the coast before it could be detected 4 mi. out to sea, and the remainder of the flights do not imply such a rapid landward movement of the sea breeze as one might anticipate from an inspection of figure 10. Furthermore, remember that on flights 55 and 60 there is some doubt as to whether the northward turning was associated with the sea breeze regime at all. In summary, while there is evidence that the tetroons can detect the position of the sea breeze front at sea before its arrival at the coast, the present data do not yield a quantitative estimate of the speed of movement of the sea breeze front and the orientation thereof.

Another matter worthy of investigation involves the possible influence of the Coriolis force upon the tetroon trajectories. Several previous studies, for example, those of Schmidt [15] and Defant [3], have indicated that the direction of the sea breeze wind veers with time. Figure 11 shows, as a function of local time, the bearing of the end point of tetroon trajectories on sea breeze days. There is considerable scatter, but during the hours from about 1700 to 2200 there is a tendency for the bearing to shift with approximately the pendulum day period, or what is the same thing, to shift in accord with the rate of rotation of the earth about the local vertical. These results are not particularly exciting since similar information could be obtained from fixed-point wind data. What is of interest is to see whether the tetroon trajectory direction itself veered with time. Therefore, one-half hour average trajectory directions were determined along those flights which were released between approximately 1800 and 2100 on sea breeze days, and were tracked for at least 1½ hr. Flights 17 and 18 were excluded from examination because, as mentioned previously, they were involved with a wind regime induced by a thunderstorm. Figure 12 shows trajectory direction as a function of time after release for the remainder of the flights. All the trajectories do exhibit a veering in direction with time and, on the average, at a rate nearly in accord with the pendulum day period. The tendency for the veering to increase with time after release suggests that the different frictional effects of land and sea may also have been playing a role here, although such a frictional influence is not apparent along the trajectories on non-sea breeze days (fig. 4).

A complete analysis of the sea breeze flow entails a comparison of tetroon-derived wind direction and the (surface) geostropic wind direction. Inasmuch as on sea breeze days the individual tetroon trajectories frequently changed direction, it is not appropriate to take the mean trajectory direction for the whole flight as was done for the non-sea breeze days. Instead, the average direction of tetroon movement was obtained for a 1-hr. time interval and comparison was made with the geostrophic wind

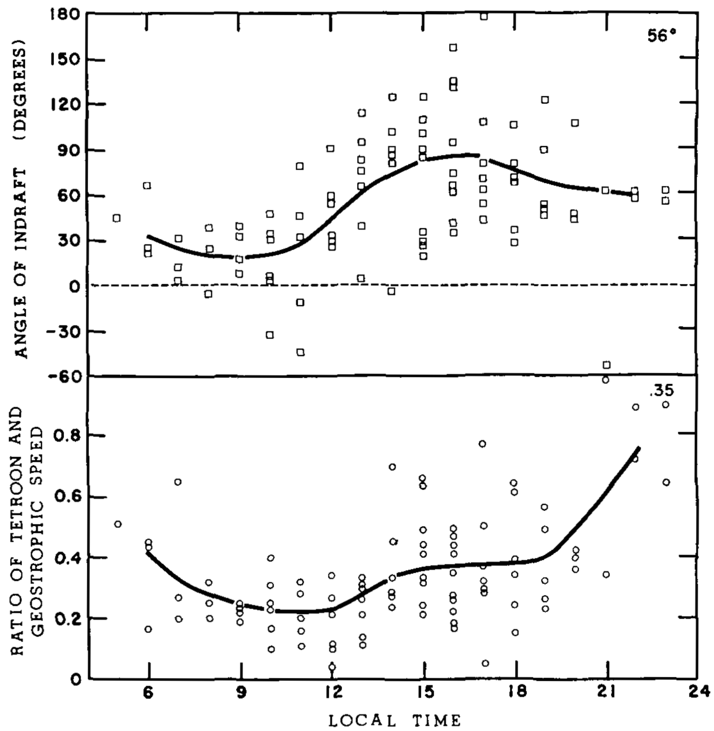

FIGURE 13.—On sea breeze days, (top) surface geostrophic wind direction minus tetroon flight direction, or angle of indraft, and (bottom) the ratio of tetroon-derived speed and geostrophic speed, both as a function of time of day. The individual points represent hourly comparisons, the solid line a smoothed average of the individual comparisons. The mean of all cases is plotted in the upper portion of each diagram.

obtained (at the midpoint of this time interval) from the four stations ACY, MIV, PNE, and NEL, as previously. The top diagram of figure 13 shows these values of geostrophic direction minus tetroon direction (angle of indraft) as a function of time of day. On sea breeze days the average angle of indraft was 56°, with the smoothed average varying from 18° at 0900 to 85° at 1700. Therefore, during the afternoon, the angle of indraft was 1½ times as large on sea breeze days as on non-sea breeze days, and the maximum angle of indraft tended to occur later in the day. Figure 13 shows, in addition, that on sea breeze days the angle of indraft quite often exceeded 90°, that is, the wind had an antigeostrophic component. As a matter of interest it should be noted that, during sea breeze days, the geostrophic wind itself (as determined from the four stations ACY, MIV, PNE, and NEL) had a diurnal variation, with the average geostrophic wind direction varying from west-northwest at 0600 to west-southwest at 1800 and then back to west-northwest again. This variation in direction is in accord with the observation, made during the experiment, that a trough of low pressure tends to form just inland from the coast during the afternoon hours on sea breeze days.

The bottom diagram of figure 13 shows the ratio of

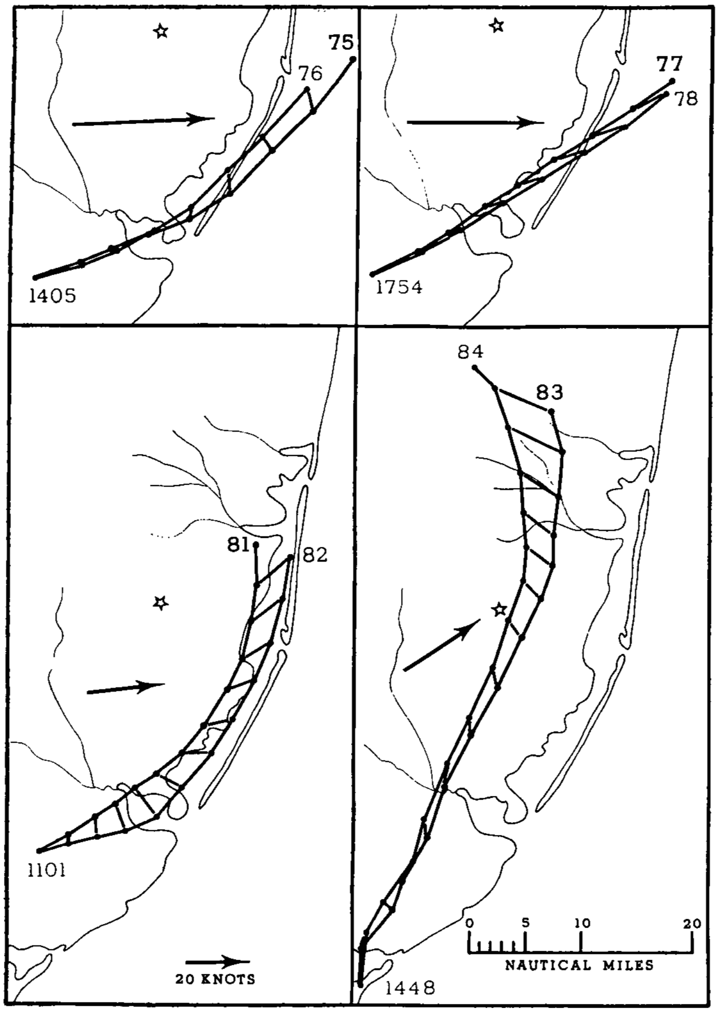

FIGURE 14.—Trajectories of tetroon pairs released (nearly) simultaneously from Atlantic City Airport and from Ocean City. Thin solid lines (isochrones) connect tetroon positions (15-min. intervals) at the same time. The arrow indicates the average geostrophic wind during the time of the flights, the star the location of a lookout tower on relatively high ground. Flight numbers indicated at ends of trajectories, release times at launch sites.

tetroon-derived wind speed and (surface) geostrophic speed during sea breeze days. This ratio averaged 0.35 but varied from a value of 0.22 at 1100 to a value exceeding 0.40 between 2100 and 0600. Comparison with figure 5 shows that this ratio is distinctly less for sea breeze days than for non-sea breeze days. This reduction comes about because the mean tetroon speed was less on sea breeze days (10.8 kt.) than on non-sea breeze days (17.3 kt.). The diurnal variation in geostrophic speed on sea breeze days was relatively slight, the average value increasing from 29 kt. at 0600 to 37 kt. at 1800. As mentioned earlier, the relatively large mean value of the geostrophic wind may indicate a slight error in the pressure readings at ACY, NEL, or both.

6. TETROON PAIRS AND RELATIVE DIFFUSION

The sequential and simultaneous release of tetroons provides data for the study of atmospheric diffusion. While the analysis of data of this type may appear out of order in a paper which, basically, involves a discussion of the sea breeze, it is of interest to compare the diffusive capacity of the atmosphere on sea breeze and non-sea breeze days. In the following section the diffusion to be expected (during sea breeze and non-sea breeze regimes) from a continuous point source is estimated from the sequential release of tetroons. In this section the diffusion from an instantaneous point source is estimated, based upon the simultaneous release of tetroon pairs on non-sea breeze days at Atlantic City and on sea breeze days within the Los Angeles Basin.

On four occasions, pairs of (nearly) simultaneously released tetroons were tracked for a considerable distance at Atlantic City, as shown in figure 14. The tetroons were not released exactly at the same time (table 1) because there was difficulty in differentiating between the two transponder signals despite a difference in frequency. Consequently, a few minutes were allowed to elapse between the release of the two balloons. The paired flights 81 and 82 are of interest in that flight 82 moved faster than flight 81, perhaps because of the different frictional effect of land and water. The backing of these two trajectories with time suggests a sea breeze influence, which was also detectable in subtle changes in wind direction at the Marina on July 20 (fig. 4). One might also note that the trajectories of flights 75 and 76 clearly intersected after 45 min. and there was a similar tendency on flights 83 and 84. On the latter two flights the turn toward the west was associated with a frontal trough which was moving slowly toward the south. The exact location of the front is not easily pinpointed, but the available evidence suggests that the tetroons were north of the surface position of the front when the trajectories terminated.

One of the great advantages of paired releases is that, if the tetroons can be ballasted to float at exactly the same mean altitude, the spread of the trajectories with time and distance yields information concerning relative diffusion, or the spread from an instantaneous point source. However, in order to effect a comparison with conventional puff data one must make use of the relation which states that the variance of a distribution of particles is proportional to the sum of the squares of the distances between all possible pairs of particles (Brier [1]). Of course, in our case we have available only one pair of particles, namely, the tetroons, and it turns out that under these conditions the standard deviation is given by the distance between the tetroons divided by the square root of two. It is obvious that many tetroons pairs will have to be released before representative relative diffusion data can be obtained in this way. So far in the tetroon program, one paired release at Cincinnati (Pack [1]), four paired releases at Los Angeles (Pack and Angell [12]), and the four pairs at Atlantic City are suitable for study.

Figure 15 shows the variation with downwind distance

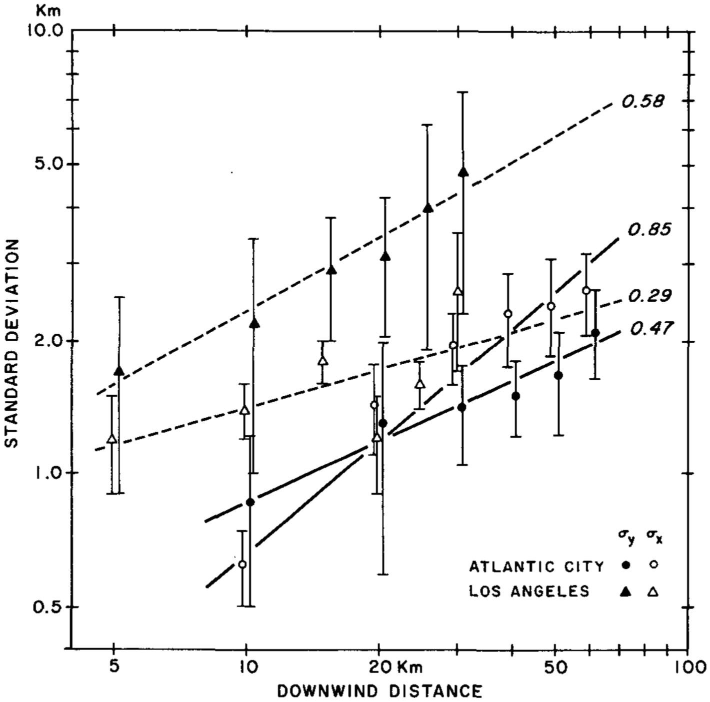

FIGURE 15.—Variation with downwind distance of the lateral and longitudinal standard deviation of a puff as derived from the simultaneous release of tetroon pairs at Atlantic City and within the Los Angeles Basin. The straight lines are regression lines; the numbers indicate the power of the downwind distance to which the standard deviation is proportional. Vertical bars extend one standard deviation of the mean above and below the mean.

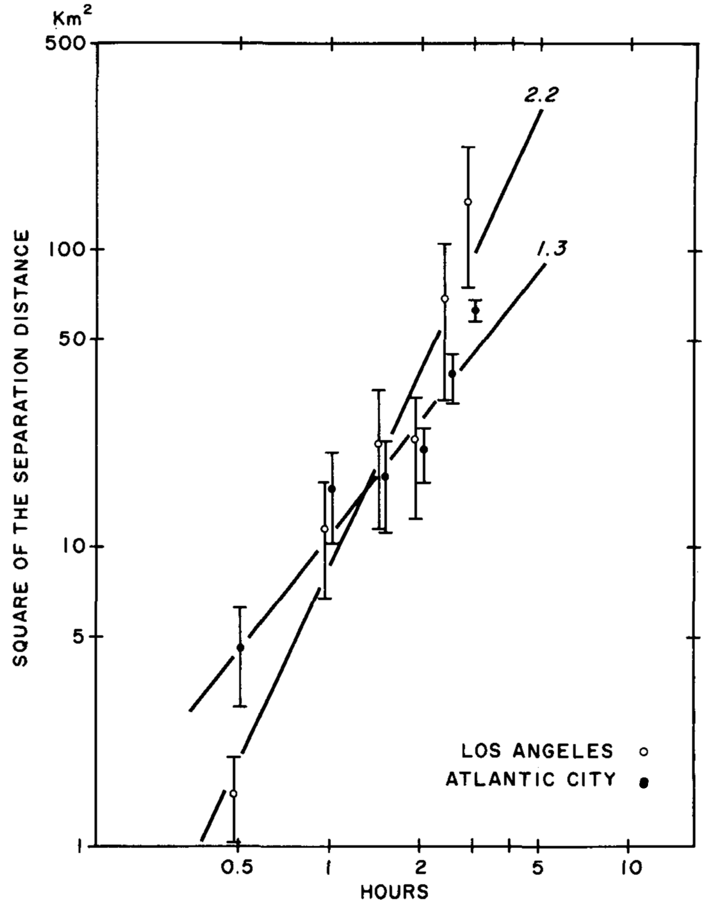

FIGURE 16.—The square of the (horizontal) separation distance between pairs of simultaneously released tetroons as a function of time after release. The straight lines are regression lines; the numbers indicate the power of the time after release to which the square of the separation distance is proportional. Vertical bars extend one standard deviation of the mean above and below the mean.

of the lateral standard deviation (σ_y) and longitudinal standard deviation (σ_x) based upon the simultaneous release of pairs of tetroons at Atlantic City and Los Angeles. The value of σ_y obtained within the Los Angeles sea breeze is about twice that obtained on non-sea breeze days at Atlantic City. However, with only four observations at each site, the standard deviation of the mean is large, and hence the difference between the σ_y's obtained at the two sites is not statistically significant. The regression lines of σ_y upon downwind distance are similar at the two sites and suggest that, over downwind distances from about 10 to 50 km., the σ_y (of a puff) varies as approximately the 0.5 power of this distance.

On the basis of conventional experiments (i.e., successive photographs of a puff of smoke), σ_y at a downwind distance of 100 m. is found to vary from approximately 1 m. in stable conditions to 15 m. in unstable conditions.[2] If these values are related to the values obtained from the tetroons it is found (table 2) that, over the downwind distance from 0.1 to 10 km., σ_y varies as about the three-halves power of this distance, if the tetroon flights are assumed to have been made under stable conditions, and as about the first power if made under unstable conditions. Inasmuch as the flights were all made at low level during the day, unstable conditions most likely did prevail, and thus these data suggest that σ_y varies in proportion to approximately the first power of the downwind distance out to distances of the order of 10 km., but thereafter varies in proportion to about the 0.5 power.

The variation of longitudinal standard deviation (σ_x) with downwind distance at the two launch sites is not so

TABLE 2.—*The power of the downwind distance to which the lateral and longitudinal standard deviations of a puff are proportional (over the downwind interval from 0.1 to 10 km.), as estimated from a collation of conventional puff diffusion data (obtained under stable and unstable conditions) with the results obtained from tetroon pairs at Atlantic City and Los Angeles:*

	Lateral direction		Longitudinal direction	
	Stable	Unstable	Stable	Unstable
Atlantic City	1.48	0.87	1.38	0.81
Los Angeles	1.66	1.08	1.57	.98
Average	1.57	.98	1.48	.90

[2] David Slade, Personal communication.

consistent. At Atlantic City, at distances exceeding 20 km., σ_x is larger than σ_y, but not significantly so. At Los Angeles, at downwind distances between 5 and 30 km., the reverse is true, but again the difference is not significant. The most striking difference between the two launch sites lies in the power of the downwind distance to which σ_x is proportional, 0.85 at Atlantic City but only 0.29 at Los Angeles (based on regression lines). This difference presumably reflects the uncertainties involved in statistics derived from such limited data. Note that if we average these two powers, we obtain a value of 0.57, not very different from the average power of 0.52 obtained for σ_y. Therefore, since the flights were made under generally unstable conditions, there is also a tendency for σ_x to vary as about the first power of the downwind distance out to distances of the order of 10 km. (table 2), but thereafter to vary in proportion to about the 0.5 power.

It is of interest, in addition, to analyze data of this type as a *function of travel time or time after release.* Figure 16 shows, for each launch site, the square of the (horizontal) separation distance between pairs of (nearly) simultaneously released tetroons as a function of time since release. Based on regression lines, the square of the separation distance is proportional to the 1.3 power of the time for flights from Atlantic City on non-sea breeze days, but to the 2.2 power for flights from Los Angeles on sea breeze days. Thus, while the overall impression is that, over travel times of about ½ to 3 hr., the square of the separation distance is proportional to a power of the time somewhat less than two, the two launch sites yield such different values of this power that one must presume that insufficient data have been obtained at either launch site to stabilize the statistics and to permit much generalization.

Collation of conventional relative diffusion data with the tetroon data gives the results presented in table 3. With the assumption that the tetroon flights have been made under unstable conditions, the square of the separation distance appears to be proportional to a power of the time somewhat less than two also at the shorter travel times. Thus, there is little evidence for a change in the power of the time to which the square of the separation distance is proportional, at least for travel times as large as 3 hr.

TABLE 3.—*The power of the time to which the square of the horizontal separation distance between particles is proportional (for the time interval from 10 or 20 sec. to 0.5 hr.), as estimated from a collation of conventional puff diffusion data (obtained under stable and unstable conditions at different mean wind speeds) with the results obtained from tetroon pairs at Atlantic City and Los Angeles.*

	5 m. sec.$^{-1}$ wind speed		10 m. sec.$^{-1}$ wind speed	
	Stable	Unstable	Stable	Unstable
Atlantic City	3.0	1.9	2.7	1.8
Los Angeles	2.9	1.6	2.6	1.5
Average	3.0	1.8	2.6	1.6

7. DIFFUSION FROM A CONTINUOUS POINT SOURCE

In order to estimate through the use of tetroon trajectories, the lateral standard deviation (σ_y) as a function of downwind distance for a continuous point source, we have adopted the technique of Brier [1] mentioned in the previous section. To repeat, this technique involves the realization that the variance of a distribution of particles is proportional to the sum of the squares of the differences between all possible pairs of particles. What has been done in this case was to determine the distance between pairs of (non-simultaneously released) tetroons at downwind intervals of 5 km. for all pairs whose difference in release time did not exceed 24 hr. The lateral standard deviation as a function of downwind distance was next evaluated, by electronic computer, for all possible trajectory series through the use of the above proportionality. There is considerable redundancy here in that one series differs from another series only through the addition or subtraction of a single trajectory. However, the results should be representative since all possible trajectory series have been taken into account. In the following the data have been divided into two groups according to whether the tetroon trajectories were obtained on sea breeze days or on non-sea breeze days. We have also divided the data according to whether the tetroons were released over time intervals of between 0 and 6 hr., between 6 and 12 hr., between 12 and 18 hr., and between 18 and 24 hr. To a first approximation, then, the data refer to time periods of tetroon release (t_r) of 3, 9, 15, and 21 hr.

Figure 17 shows the lateral standard deviation (σ_y) derived from tetroon flights at Atlantic City on sea breeze and non-sea breeze days. These values of σ_y are relatively large because there is no constraint to intersect a fixed sampling grid of limited arc, as is frequently the case with bulk tracer experiments. Two points are worthy of emphasis. First, for non-sea breeze days, and for release intervals of the order of 3 hr., σ_y is relatively small and quite comparable with the values obtained from conventional tracer experiments (ratio of σ_y to downwind distance approximately 0.1). This would be expected since, with steady winds, only small-scale turbulence provides the diffusing mechanism. Second, σ_y is larger for sea breeze days than for non-sea breeze days, particularly for the shorter release intervals. This observation, combined with the relatively small increase in σ_y with increase in release interval on sea breeze days, verifies the intuitive expectation that in such local, oscillatory regimes the diffusion is due to relatively high frequency wind variations and not due to synoptic influences. On the other hand, the relatively large increase in σ_y with increase in release interval on non-sea breeze days indicates the diffusive effect of low frequency wind variations associated with disturbances of synoptic scale. In terms of a power-spectrum representation, the trajectories on sea breeze days would yield a peak (in the lateral velocity variance) at a period of 12 hr. or less, whereas on non-sea breeze

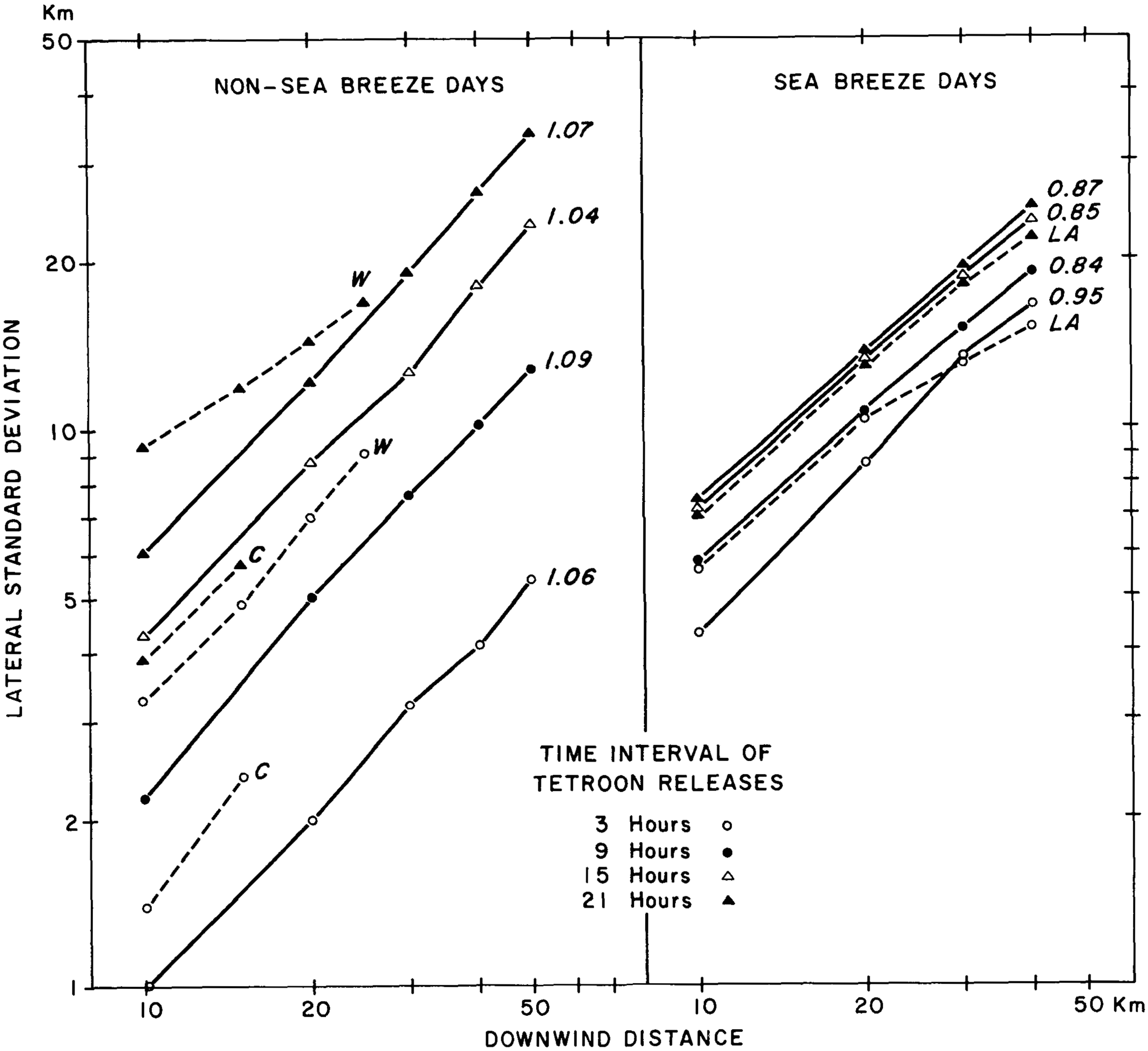

FIGURE 17.—Lateral standard deviation as a function of downwind distance and time interval of tetroon release during sea breeze and non-sea breeze days at Atlantic City (solid lines). The dashed lines represent similar data obtained at Cardington, England (C), Wallops Island, Va. (W), and Los Angeles, Calif. (LA). The numbers indicate the power of the downwind distance to which the lateral standard deviation is proportional.

days the variance would continually increase with decrease in frequency and a peak would never be attained with trajectory data of such limited duration. The practical applications of figure 17 reside in the evidence that, if one wishes to obtain a large lateral spread of a pollutant for relatively short release times, one should release in a sea breeze rather than in a non-sea breeze regime.

For comparison with the Atlantic City data, lateral diffusion data derived from tetroon flights at Cardington, England (C), Wallops Island, Va. (W), and Los Angeles, Calif. (LA), have also been plotted in figure 17, but only for tetroon release intervals (t_r) of 3 and 21 hr. One might expect the lateral diffusion data obtained at Cardington and at Wallops Island (in winter) to be similar to

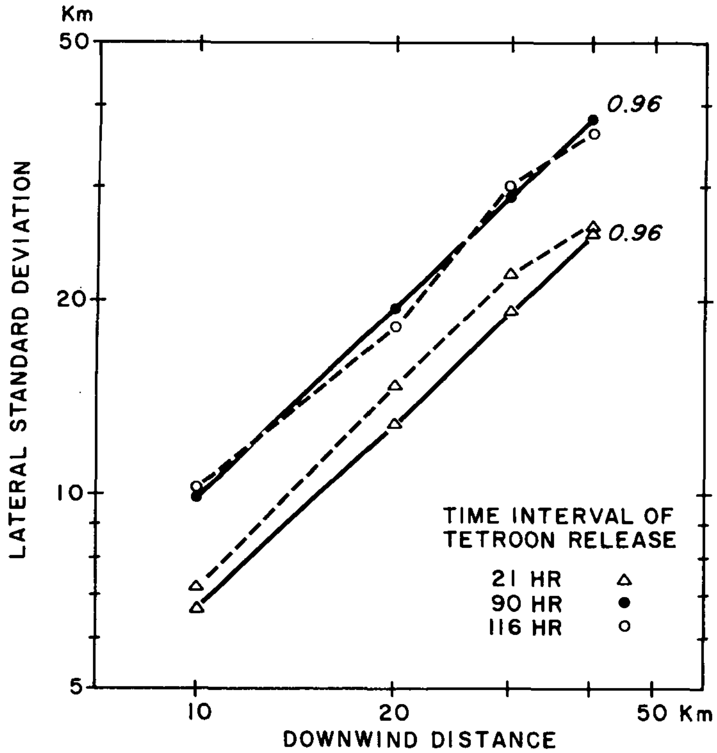

FIGURE 18.—Lateral standard deviation as a function of downwind distance and time interval of tetroon release for flights from Atlantic City (solid lines) and from Long Beach within the Los Angeles Basin (dashed lines). The numbers indicate the power of the downwind distance to which the lateral standard deviation is proportional.

those obtained at Atlantic City on non-sea breeze days, and indeed, for $t_r=3$ hr. the Cardington data are similar to the Atlantic City data and for $t_r=21$ hr. the Wallops Island data are similar to the Atlantic City data. However, at neither Cardington nor Wallops Island does σ_y vary so rapidly with t_r as at Atlantic City. One might expect, in addition, that the lateral diffusion data obtained within the sea breeze regime of the Los Angeles Basin would be similar to the data obtained at Atlantic City on sea breeze days, and in this case the agreement is extremely good, as noted from the right hand diagram of figure 17.

The numbers within the diagrams of figure 17 represent, over the given downwind distance, the power of this distance to which σ_y is proportional. This power averages slightly more than one on non-sea breeze days and slightly less than one on sea breeze days. A similar power was obtained at Cardington, Wallops Island, and Los Angeles. It might be recalled that powers on the order of 0.9 have been obtained for diffusion experiments over downwind distances of hundreds of meters and hundreds of kilometers. A possible explanation for the proportionality of σ_y to about the 0.9 power of the downwind distance, regardless of the scale of motion under investigation, had been presented by Pasquill ([13], p. 175).

It is worthwhile to examine these data from the point of view of the power of the tetroon release interval (t_r) to which σ_y is proportional. On non-sea breeze days the ratio of σ_y to downwind distance at Atlantic City varies from 0.1 to 0.5 for values of t_r varying from 3 hr. to 21 hr. This yields a σ_y proportional to the 0.93 power of t_r. However, at Cardington, σ_y is proportional to only the 0.49 power of t_r (for these same release intervals), while at Wallops Island the factor of proportionality is 0.43. Consequently, the non-sea breeze trajectories at Atlantic City are unique in yielding such a rapid increase in σ_y with increase in t_r. On the other hand, for values of t_r varying from 3 to 21 hr., the trajectories at Atlantic City on sea breeze days yield a σ_y proportional to the 0.22 power of t_r. The latter is in good agreement with the power of 0.16 obtained in the sea breeze regime of the Los Angeles Basin.

Inasmuch as tetroons were released continuously, day and night, for a period of 90 hr. at Atlantic City, it is possible to extend, in time, the investigation relating σ_y and t_r. The variation with downwind distance of σ_y for $t_r=90$ hr. (these 90 hr. embrace both sea breeze and non-sea breeze days) and for $t_r=21$ hr. at Atlantic City is shown in figure 18. These values indicate a σ_y proportional to the 0.26 power of t_r. At Long Beach, within the Los Angeles Basin, tetroons were released continuously for a period of 116 hr. The values of σ_y derived therefrom and from 21-hr. release intervals, are also shown in figure 18. These latter values indicate a σ_y proportional to the 0.18 power of t_r. These two values of the power are reasonably compatible, especially when it is recalled that trajectories on sea breeze and non-sea breeze days are interspersed in the Atlantic City data.

In summary, within sea breeze regimes, σ_y appears to be proportional to about the 0.2 power of t_r for quite wide ranges of t_r. Within synoptic regimes, however, σ_y is proportional to powers of t_r ranging from 0.4 to nearly 1.0.

8. CONCLUSION

Because of several factors, the utilization of tetroons to study the sea breeze at Atlantic City was not as successful as originally hoped for. These factors include a poorly defined sea breeze regime during much of the experiment, the lack of a suitable ship for offshore tetroon releases, and, most important, the inability to obtain accurate tetroon heights. Nevertheless, the investigation did point up the usefulness of tetroons for obtaining data at sea and at some height above the ground, and the diffusion statistics derived from the trajectories are not easily obtained in any other way. On the basis of this experiment it is suggested that the use of tetroons to study atmospheric phenomena requires accurate tetroon-height data to resolve the complex interrelations. Intensive efforts are now being made to develop an inexpensive, light-weight, pressure-sensing device for this purpose.

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